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Engineering process and cost model for a conventional corn wet milling facility☆

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ABSTRACT

Conventional wet milling of corn is a process designed for the recovery and purification of starch and several coproducts (germ, gluten, fiber and steep liquor). The total starch produced by the wet milling industry in the USA in 2004 equaled 21.5 billion kg, including modified starches and starches used for sweeteners and ethanol production.

Process engineering and cost models for a corn wet milling process (for steeping and milling facilities) have been developed for a "generic" processing plant with a capacity of 2.54 million kg of corn per day (100,000 bu/day). The process includes grain cleaning, steeping, germ separation and recovery, fiber separation and recovery, gluten separation and recovery and starch separation. Information for the development of the models was obtained from a variety of technical sources including commercial wet milling companies, industry experts and equipment suppliers. The models were developed using process and cost simulation software (SuperPro Designer®) and include processing information such as composition and flow rates of the various process streams, descriptions of the various unit operations and detailed breakdowns of the operating and capital cost of the facility.

Based on the information from the model, we can estimate the cost of production per kilogram of starch using the input prices for corn and other wet milling coproducts. We have also used the model to conduct a variety of sensitivity studies utilizing modifications such as feedstock costs, corn compositional variations, and the sale of wet corn gluten feed. The model is also being used as a base-case for the development of models to test alternative processing technologies and to help in the scale-up and commercialization of new wet milling technologies.

This model is available upon request from the authors for educational, non-commercial and research uses.

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1. Introduction

Conventional wet milling of corn is a process designed for the recovery and purification of starch and several coproducts. The US corn wet milling industry can trace its beginnings back to 1844 when Thomas Kingsford, working at Wm. Colgate & Company in Jersey City, NJ, convinced his employer to try a new alkali process for extracting starch from corn. This plant became the world's first dedicated corn starch plant. Kingsford built his own corn wet milling facility a few years later in Oswego, NY (CRA, 2000). Many changes in processing and equipment have occurred over the last 160 years. The total starch produced by the wet milling industry in 2004 equaled 21.5 billion kg, including modified starches and starches used for sweeteners and ethanol production (CRA, 2005).

Prior to the 1880s, the corn refining industry simply discarded fiber, germ and protein from corn. Refiners began realizing the value of non-starch corn products to turn them into animal feed and extract corn oil from germ. These extractions not only decrease the production price of starch but also decrease starch loses and increased its quality.

Currently the end products of the wet milling process are starch slurry, germ, corn gluten feed and corn gluten meal. Starch is the primary product of the process (Blanchard, 1992). It is used with minimal further processing as a food additive or as an adhesive. Economically more important is its conversion to corn sweeteners and ethanol. Typical starch slurry leaving the mill house has 60% moisture content.

The germ is used for corn oil production and the resulting meal used for animal feed or added back to the corn gluten feed. Corn oil, the most valuable component of the corn kernel, is recovered from the germ by expelling or more often by solvent extraction. More than a million tonnes of corn oil are produced annually in the United States (Gunstone, 2006). Typical germ contains 48% oil, 13% protein, 12% starch, 2% ash and 3% moisture.

Corn gluten feed is the fiber rich component removed in the wet milling process. It is a high fiber, low protein feed used as energy, protein and fiber source for beef cattle. Corn gluten feed is produced by combining concentrated steepwater with the fiber during the separation process. This coproduct typically contains 60% fiber and 20% protein (White and Johnson, 2003).

Corn gluten meal is the high protein, low fiber fraction extracted during the wet milling process. It is used as an energy, protein, vitamin and mineral source for poultry and swine. The final corn gluten meal has typically 60% protein and 10% moisture (Blanchard, 1992; CRA, 1989).

Computer simulation models have been used successfully to understand processes and the physical and economical implications of experimental modifications. We developed engineering and economic models for the corn wet milling process (steeping and milling facilities) as research tools to help in the evaluation and optimization of the process and to aid in future process development. The models were developed using the software SuperPro Designer®, Version 7.0 (Intelligen Inc., Scotch Plains, NJ), based on previous models (Johnston et al., 2004) developed originally in Aspen Plus® (Aspen Technologies Inc., Cambridge, MA) and Microsoft Excel (Microsoft Corporation, Redmond, WA). Information on the corn wet milling process was obtained from various technical sources including commercial wet milling companies, industry experts and equipment suppliers.

2. Process model description

The conventional wet milling process includes many steps for the recovery and purification of starch and all coproducts (germ, gluten meal, and corn gluten feed). Our model is based on a "generic" processing plant with a capacity of 2.54 million kg of corn per day. The process and model is divided in six main sections, which include grain handling, steeping, germ separation and recovery, fiber separation and recovery, gluten separation and recovery and starch washing and recovery (Fig. 1). The unit operations in the model are identified by a number ID based on each one of the 6 sections (100's for grain handling, 200's for steeping, etc.) and the type of operation (one or two letters to identify equipment). All wet milling plants in US or around the world are quite similar in steeping and milling facilities. Depending upon the final end product (modified starch, glucose, High Fructose Corn Syrup (HFCS), ethanol or other fermentation products), downstream differences (after milling) exist in unit operations among wet milling plants. For greater usability and consistency in wet milling unit operations, this model was designed for only steeping and milling facilities (up to starch recovery). According to individual user requirements, additional downstream processes could be added if there is a need to model more specific products. Product yields generated from the model are shown in Table 1. The product yields are in line with information in Blanchard (1992) and from personal communication with Dorr Oliver (2002) and members of CRA. Table 2 shows the main unit operations and settings in the process model.

2.1. Grain handling

The corn is received in the facility and held in storage silos prior to cleaning. Small and large foreign matter in the corn is then removed to prevent clogging the screens, increasing viscosity during the process and affecting the quality of the finished products. This is represented in our model as a waste of 2.4% debris of total capacity. The silo in our model is sized to hold enough corn for 3 days of operation. Included in this area are also weighing and handling equipment. The cleaned corn is weighed and sent to steeping.

2.2. Steeping

The clean corn is soaked in a dilute SO_2 solution (steep acid), under controlled conditions of time and temperature. Steeping is the chemical processing step where the protein matrix is broken down to release the starch granules so they can be separated during subsequently milling. The objective of steeping is to facilitate the separation process by softening the kernel, increasing the moisture content of the grains and removing soluble matter. The overall efficiency of the wet milling process is dependent on the proper steeping of the corn. In practice, the steeping is done in a semi-continuous counter-

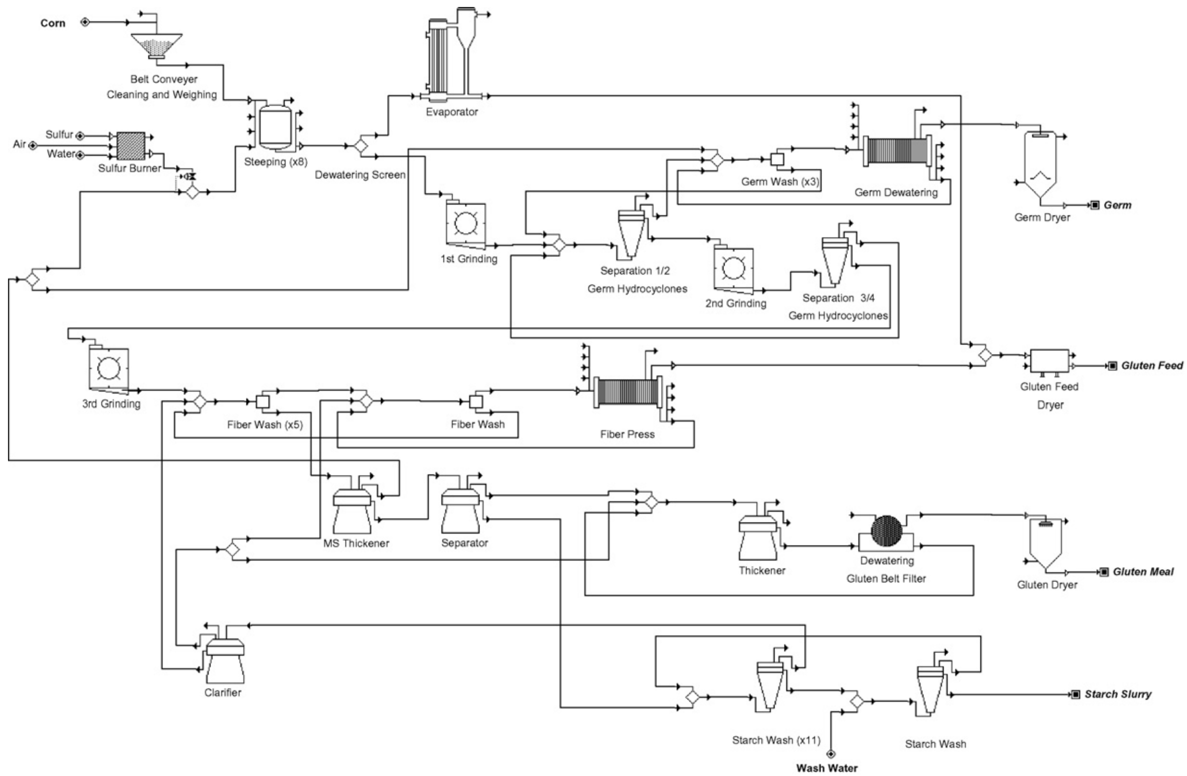

Fig. 1 – Simplified flow diagram of the corn wet milling process.

current system. During the steeping process the corn entering steeping is in contact with the most diluted, oldest SO_2 solution (light steepwater) and the oldest steeped corn is soaking in the most concentrated, freshest steepwater (steep acid). The corn does not move but the steepwater is transferred through the different tanks to go from the oldest steeped corn to the freshest. The water used for steeping is not fresh water but comes from downstream in the process; the SO_2 concentration is adjusted prior to steeping. The sulfur dioxide in our model is produced from burning elemental sulfur. During the steeping process, most of the soluble solids (about 69%) are removed and carried in the steepwater. This light steepwater (also called steep liquor) is concentrated to 50% solids, mixed with the corn fiber and dried to produce an animal feed as corn gluten feed. In our model, the corn is soaked in a group of eight stainless-steel tanks and held in the steep acid for a total of 36 h at 51 °C. The SO_2 concentration is 2000 ppm for the steep acid and 600 ppm for the light steepwater. The moisture content in the corn increases from 15 to 45% during steeping.

Table 1 – Corn wet milling product yields derived from the process model

Product	Yield (mass d.b. %)[a]
Dry germ	7.7
Gluten feed (steep water solids plus fiber)	19.4
Gluten meal	6.2
Starch	66.7

[a] Calculated on a dry weight basis after waste materials are removed.

2.3. *Germ separation and washing*

The germ is separated from the rest of the kernel after a coarse grinding. The swollen kernel is ground (first degermination) and the oil-rich corn germ is separated from the starchy slurry using four sets of hydrocyclones. The separation is based on the lower density of the germ, due to its high oil content, compared to the density of the slurry. The germ is retrieved from the overflow of the first set of hydrocyclones while the underflow continues the separation in the second set. After the first and second separations, the remaining slurry is ground again (second degermination) and any remaining germ is recovered by the last two sets of hydrocyclones. The overflows of all hydrocyclones, with the exception of the first set, are recycled to grind tanks to optimize the purity of the germ recovered. In order to achieve the desired separation, adjustments to the underflow-to-feed ratio (U/F) for the hydrocyclones are set. In our model, the U/F ratio has been set as 80, 70, 80 and 60% for the first, second, third and fourth hydrocyclones separations, respectively. The control of the specific gravity during germ separation is critical to proper recovery. Although it is possible to get a very clean separation of the germ from other components, the specific gravity is typically adjusted to allow some pericarp fiber (coarse fiber) to be co-recovered with the germ. This is done to aid in the oil extraction process because clean germ “slips” during expelling and decreases the oil extraction efficiency. The pure germ (overflow, separation 1) is washed in a series of screens using process water, dewatered to about

Table 2 – Overview of selected wet milling process equipment

Description	Detail
Belt conveyer	55.556 kg/s m loading rate/belt width
Cleaning	2.4% removed as debris
Steeping tanks	8 tanks 36 h residence time 90% volume 51 °C
Sulfur burner	2000 ppm of SO_2 in steeping tanks
Evaporator	Mechanical vapor recompression 50% solids steep liquor
Dewatering screen	DSM screen 50% overflow moisture content
Bauer mill—first grind	0.0087 kJ/s/(kg/h) specific power
Hydrocyclones 1/2	Primary germ separation
Bauer mill—second grind	0.0016 kJ/s/(kg/h) specific power
Hydrocyclones 3/4	Secondary germ separation
Screw press	Germ dewatering 50% final moisture content
Fluidized bed dryer	Germ dryer 0.07 kg natural gas/kg evaporated 3% moisture content
Disc mill—third grind	0.0116 kJ/s/(kg/h) specific power
Dewatering screen	Fiber wash DSM screens 76% overflow moisture content
Screw press	Fiber press 60% final moisture content
Rotatory dryer	Gluten feed dryer 0.07 kg natural gas/kg evaporated 10% final moisture content
Centrifuge	Clarifier 3744 l/min throughput 27% (w/w) solids in underflow
Centrifuge	Mill starch (MS) thickener 7378 l/min throughput 25% (w/w) Solids in underflow
Centrifuge	Primary separator 3012 l/min throughput 34% (w/w) solids in underflow
Centrifuge	Gluten thickener 2884 l/min throughput 16% (w/w) Solids in underflow
Rotatory drum vacuum filter	Gluten belt filter 60% final moisture content
Ring dryer	0.07 kg natural gas/kg evaporated 10% final moisture content
Hydrocyclone	Last stage of starch washing 4552 l/min throughput 1.3 kg fresh water/kg of dry corn

50% solids in a screw press and dried to a final moisture content of 3% in a fluidized bed dryer. In the model, the screens are represented by two-way component splitters and the screw press by a plate and frame filter. The dry germ is produced in our model at a rate of 7031 kg/h with a final lipid content of 43.7% on a dry weight basis and a protein content of 10.45%. The underflow of the last set of hydrocyclones (separation 4) continues the coproduct separation process.

2.4. *Fiber separation and recovery*

The degermed corn slurry from the germ separation is passed over the grit screen to separate water and loose starch and gluten (mill starch) from the fiber and bound starch and gluten. The mill starch is sent further in the process, for the separation of gluten and starch. The remaining solids (fiber and bound starch and gluten) are finely ground (third grind mill) to complete the dispersion of the starch; this milling is intended to free the starch with minimum fiber breakup. The ground slurry is then washed and separated in a series of tanks and fiber wash screens (six in our model), in a countercurrent fashion. The wash water (process water from the gluten thickener) is introduced in the last stage and it flows in a countercurrent fashion, finally coming out in the first screen with the free starch and gluten. The clean fiber is recovered in the last stage, dewatered first by a screen to a moisture content of 75% and then by a screw press to a final moisture of 60%. This fiber is usually combined with the concentrated steep liquor, dried in a rotary drum drier to 10% moisture and sold as corn gluten feed. The final corn gluten feed (19,000 kg/h in our model) has a protein content of approximately 20% on a dry weight basis.

2.5. *Gluten separation and recovery*

The gluten is separated from the starch by density differences in a disk stack centrifuge. Prior to the separation, the mill starch is degritted to remove any foreign particles such as sand, rust or pipe scale that might interfere with the centrifuges later in the process. The mill starch is then concentrated, to facilitate the separation, in a centrifuge called the mill-starch thickener. The thickened mill starch stream is passed to the primary centrifuge where the less-dense gluten (1.1 g/cm^3) is separated from the starch (1.6 g/cm^3). The purpose of the primary centrifuge is to obtain high-quality gluten in the overflow. The underflow, which contains the starch, some gluten and other impurities, is sent to the starch washing process. The gluten is then dewatered in three succeeding steps using a centrifuge (gluten thickener), a rotary vacuum belt filter and a ring dryer to a final moisture concentration of 10%. The gluten is sold, usually for animal feed, as corn gluten meal. The final corn gluten meal (6072 kg/h in our model) has a protein content of approximately 60% on a dry weight basis and contains xanthophylls that give it a yellow color.

2.6. *Starch washing and recovery*

The crude starch is washed in a series of small hydrocyclones, grouped in stages, in a countercurrent fashion. The wash water enters the system in the last washing stage, where the starch exits the process. During the washing, the underflow continues to the next stage while the overflow recycles back to the previous stage. The water with the impurities leaves the system at the first stage and it is recycled back to the middlings clarifier to concentrate the stream for further gluten and fiber separations. The overflow from the middlings clarifier contains the lowest concentration of solids in the system except for the fresh water. Our model shows the system with 12 hydrocyclone washing stages, each one with its own pump, using 2.3 kg of fresh water per kg of dry starch. The final starch slurry (144,000 kg/h) contains 60% moisture content with less than 1% of impurities.

3. Cost model description

A cost model of the dry grind ethanol process was developed to estimate the capital and production costs for the processing of corn in a wet milling facility. The data in the model was obtained from operators of wet milling facilities, equipment suppliers, pricing and cost data reported by trade organizations and government agencies and relevant publications. The assembling and analysis of this data was done using the cost estimating program in Superpro Designer®, using generally accepted methods for conducting conceptual economic evaluations for industrial processes (AACE International, 1990). The costs are not specific to any one plant since each facility has its own unique characteristics, but it is representative of currently operating wet milling processes in the United States with capital and operating costs typical of 2007.

The economic results in the model are linked to the physical flows and unit operations defined in the process simulation model. The results provide an understanding of the costs associated with the wet milling industry and help in the evaluation of the impact of wet milling costs due to changes in the composition and costs of the feedstock, products and processing operations of the process.

3.1. *Equipment and capital costs*

Corn wet milling facilities utilize milling equipment to break the structure of the corn kernel. Hydrocyclones, centrifuges and screens are used to separate components. Evaporators, presses, filters and dryers remove water. Tanks, conveyers and pumps are used to move and store the various process streams. Specialized equipment such as the sulfur burner is used to produce SO_2 needed for steeping. The proper application of much of this equipment to the wet milling industry is very specific and resides with the technology suppliers to this industry. The equipment sizing, materials of construction, and pricing for the development of this model came from these suppliers (Personal Communications, Andritz Sprout Inc., Barr-Rosin Inc., Dorr Oliver, 2002). Additional sources of equipment information for items such as tanks and pumps came from the Richardson's Process Plant Construction Estimating Standards, the Superpro Designer equipment cost estimating parameters and our internal cost database.

Equipment costs in the model can be changed by altering the number of pieces of equipment used, by substituting different prices or by changing the inputs, outputs and other characteristics of specific equipment items. If the user changes the process characteristics of an equipment item, the cost of that piece of equipment will be adjusted thru the use of a technique referred to as cost to capacity scaling factors. An understanding of this technique can be found in various texts on cost engineering (Jelen, 1970; Remer and Chai, 1990; Dysert, 2003).

Table 3 – Capital costs by system

System	Capital costs (US$ × 1000)
Corn handling and storage	
Corn storage	3,200
Corn handling	3,400
Steeping	
Steeping system	10,300
SO_2 generation	3,200
Steepwater evaporation	4,100
Germ separation	
Milling and separation	4,700
Washing	500
Drying	5,500
Fiber separation	
Separation and washing	10,100
Drying	8,700
Gluten separation	
Separation and washing	14,400
Drying	7,200
Starch washing	
Starch washing	4,000
Total capital cost	79,300

The capital cost of the facility has been developed from the costs of the individual equipment items. An installation factor of three times the equipment cost was used to develop the capital cost. This represents the cost of all the labor, materials and engineering for the wet milling processing unit and does not include costs for items such as laboratories, office buildings or railroad tracks to the facility. Table 3 presents the capital costs of the process by section and broken down by system. Working capital and cost of money during construction are not included in the capital equipment costs. Information found in Table 3 can help identify systems or unit operations, with high capital costs, for improvement and further study.

3.2. *Operating costs*

Shelled corn is the principal feedstock and it accounts for about three quarters of the facilities operating costs. Corn prices vary over time and by location and considerable care must be taken in selecting the appropriate value for use. Pricing information in the model is based on market prices published in 2007 by the United States Department of Agriculture (Baker and Allen, 2007). Water and sulfur are two other material inputs in the process. Process water is included at a rate of US$ 0.35 per 1000 l. A small amount of sulfur is consumed in the wet milling process to produce the SO_2 described in Section 2.2. The amount of sulfur consumed and its cost are included in the model. The total cost of sulfur is less than US$ 20,000 year^{-1}.

Natural gas, steam and electricity are the utilities required for the wet milling process. The utility that is required for each piece of equipment is calculated by the model. The steam is assumed to be generated using natural gas and the costs for both natural gas and steam are based on a natural gas price of US$ 0.3516 kg^{-1}. Electrical costs are estimated at a cost of US$ 0.014 MJ^{-1} (US$ 0.05 kWh^{-1}). The unit cost of utilities can be easily changed by the user as needed.

The cost of the plant operators to run the facility has been included at 5 people per shift at an all inclusive rate of US$ 50.00 h^{-1}. Additional operating costs included in the model include plant maintenance (6% of capital costs), insurance (1% of capital costs), local taxes (2% of capital costs) and miscellaneous facility expenses at 5% of capital costs.

3.3. *Product values*

Due to the variety of possible products derived from starch, the starch slurry is chosen as the primary product in the facility modeled. The starch slurry is suitable for further processing to different products, such as dried starch, modified starch, dextrins, sweeteners or ethanol. Corn germ and two protein rich animal feeds, corn gluten meal with a 60% protein content and corn gluten feed with a 20% protein content are also produced. They are considered as coproducts by the industry and in the model. Some facilities sell a limited amount of the concentrated corn steepwater, but in this model the concentrated steepwater is blended with fiber to produce corn gluten feed. Corn gluten feed and corn gluten meal are considered commodities and their market prices are published in various sources (Baker and Allen, 2007).

Market prices for corn germ, which is used for the extraction of corn oil, are not readily available, but can be calculated from the germ's protein and oil content and current market values of crude corn oil and corn based protein feeds (Johnston et al., 2005). In the model a market value of corn germ of US$ 0.296 kg^{-1} has been used based on a crude corn oil price of US$ 0.695 kg^{-1} (USDA, 2007) and a corn gluten feed price of US$ 0.08 kg^{-1} (Baker and Allen, 2007).

3.4. *Annual and unit production costs*

Annual production costs for the production of starch in a water slurry are calculated by adding together all the annual operating costs to produce the starch slurry and its coproducts and then reducing this number by the income received from the value of the coproducts of the starch production (Table 4). The annual production costs include a depreciation allowance of 10% of the capital cost to which is based on a 10 year effective operating life for the facility with no salvage value at the end of its life, and the operating costs described in Section 3.2.

Unit production costs are calculated by prorating the total annual starch production costs (total production costs less coproduct credits US$ 89,536,000 year^{-1}) over the total annual production (463,150,000 kg/year). Since the starch is produced as a slurry that is approximately 60% water, the unit production cost is based on the dry weight of the starch in the slurry and not the entire slurry. The unit production cost for the starch in our model is equal to US$ 0.194 kg^{-1}.

Table 4 shows the total raw material cost (US$ 111,414,000 year^{-1}) being 81% of the total operating costs. The corn cost represents more than 99% of the total raw material costs. The coproduct credits (US$ 47,808,000 year^{-1}) decrease the annual starch production costs by almost 35%.

Table 4 – Annual operating and production costs

	Annual cost (US$ × 1000)/year
Operating costs	
Raw materials	
Corn	111,018
Sulfur	19
Water	377
Total raw materials	111,414
Depreciation	7,933
Facility related costs	3,467
Utilities	
Natural gas	6,840
Steam	1,695
Electricity	4,015
Total utilities	12,550
Operations labor	1,980
Total operating costs	137,344
Coproduct credits	
Corn gluten meal	19,255
Corn gluten feed	12,071
Corn germ	16,482
Total coproduct credits	47,808
Annual starch production cost (operating costs minus coproduct credits)	89,536

3.5. *Sensitivities*

Technical models such as this one are useful in providing an understanding of the physical and economic constraints of a given process. They are also powerful tools for predicting the process outputs due to changes in process inputs. In this model, the impacts of pricing and minor compositional changes on the economics of the process are easy to modify. Unit operation changes, changes in feedstock flows and significant compositional changes in the process inputs are also possible but require a good understanding of the model's operation.

In our base model we used a corn price of US$ 0.132 kg^{-1} (US$ 3.36 bushel^{-1}) which was representative of corn prices in the spring of 2007. However, corn prices will differ by time period and by geographical location. The impact of the cost of corn on the cost of production of starch is shown in Fig. 2. The cost of starch production increases proportionately with the increase in the price of corn.

To further evaluate the engineering and cost models, we tested them using the composition of a corn with higher oil content (HOC) and analyze the outcome of the model comparing it to real yield data obtained experimentally in the lab. For this exercise, the composition of the corn had to be modified as well as the flow rates of other input streams (wash water, sulfur), the conditions of certain unit operations (evaporator, germ dryer and split after steeping). The HOC has a higher germ content (15% vs. 7.6% d.w.b.) and therefore lower fiber, gluten, soluble solids and starch content (61% vs. 66.5% d.w.b. for starch). The changes occurring throughout the process from the HOC increase the operating costs (mainly additional germ drying costs) by less than 0.3% (US$

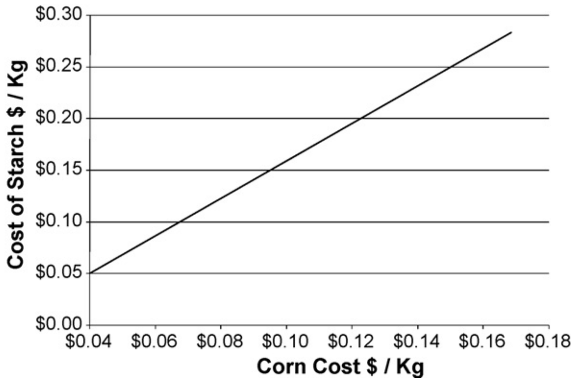

Fig. 2 – Impact of corn price on starch production cost.

267,000), but decreased the plant capital cost by 3.4%. The analysis of the impact on profitability shows the large increase in the sale of the germ more than offsets the increased operating costs and the decreased income from the starch, corn gluten feed and corn gluten meal. The net production income of the process (revenues less production costs) increases by US$ 3,427,000 or slightly over 3%.

4. Conclusions

A Technical Cost Model was developed for a corn wet milling processing plant with a capacity to process 2.54 million kg of corn per day. This model can be used in general as a tool to understand better the wet milling process and the cost issues associated with it. We use the model to conduct sensitivity studies using modifications like feedstock costs, variations in corn composition and sale of wet corn gluten feed. These and similar results contribute to the improvement of the process and the reduction of costs. Additionally, the process simulation model is currently being used to test alternative wet milling processing technologies and to predict the impact of those modifications.

Several areas have strong potential for future wet milling research. The removal of sulfur and the benefits/issues that this could have on processing and the coproduct composition could be very important for health and environmental effects. Another potential research area is the incorporation of membrane filtration technologies into the coproduct recovery processing and evaluation of the energy reduction potential they may offer. In each research area, the presented model should prove useful as a baseline comparison and a starting point for modifications.

4.1. *Model availability*

This model is available upon request from the authors for educational uses and non-commercial research to study the wet milling process and to show the impact of changes in the costs of starch and coproducts. It is not intended to replace a customized process design package. The model requires the use of SuperPro Designer®, Version 7.0 or later. A free copy of this program can be used to view the model and may be downloaded form the Intelligen website (www.intelligen.com).

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